Time, Space And Fish Scales: Applications of Retrospective Environmental Data to Fisheries Research

Richard H. Parrish, Pacific Fisheries Environmental Group, Southwest Fisheries Science Center, 1352 Lighthouse Avenue, Pacific Grove, CA 93950-2097

Biologists often tend to ignore time and space scales when they design field programs established to support fishery management. In many cases there is a mismatch between the time and space scales addressed by the field research programs and those utilized for the development of the retrospective models that are used to manage the studied populations. Large marine fisheries field programs usually expend the bulk of their research dollars on micro-scale observations taken on mesoscale grids. In contrast, fishery models developed for management purposes are almost exclusively statistical models which attempt to describe what has happened in the past and then use these statistical relationships in combination with recent observations to establish harvest guidelines or quotas for the upcoming fishing season.

The environmental data taken during field surveys is seldom used for retrospective analyses and fishery modeling. The environmental time series these analyses and models most often utilize tend be routinely monitored meteorological and oceanic parameters which represent factors which are annual in time (i.e., one value per year) and regional in space (i.e., the entire habitat or spawning habitat of the stock). However, the actual data used are often proxy values for these scales. For example, the annual time scale may be represented by a two month average temperature representing the environmental conditions which occur during a spawning season. The spatial scale is generally assumed to represent conditions over a regional spatial scale; however, the data used are often derived from a single shore station and are therefore micro-scale proxy indices for the larger spatial scale.

One of the limiting factors associated with retrospective environmental data needs is the lack of long time series which are temporally unbiased. This generally excludes remotely sensed environmental data as well as data taken from large process oriented field studies, suggesting that NMFS is not a likely source of environmental data for retrospective analyses. For example, the temperature at Scripps Pier has been used for at least ten times as many retrospective studies as the temperatures taken in the CalCOFI field program. For retrospective uses, the cost/benefit ratio for fisheries management of the Scripps Pier temperatures is easily two orders of magnitude higher than the CalCOFI temperatures and incalculably higher than the remotely sensed temperatures.

Time Scales

Biological processes naturally occur over a wide range of time scales, from behavioral responses to individual storms to extinctions caused by factors operating on geological time scales. For the purposes of this report I have classified time into four usable categories; weather, seasonal, inter-annual and regime scales (Table 1).

From a marine fisheries perspective, weather scale effects are primarily storm related and wind is the most important factor, although flooding may be a major factor for marine species with estuarine life history stages. Events at this scale have generally limited affects on adult marine fishes and are primarily associated with behavioral responses and microscale distribution changes. However, storms can have a major effect on early life history stages and in fact a major fishery paradigm is based on factors which occur at this time scale.

Seasonal scale environmental effects, that is effects which occur over a several month period (i.e., a spawning season), are of major concern in many fisheries. The environmental factors operating at this time scale are quite broad and include transport, upwelling of nutrients, spawning season temperatures, winter turbulent mixing, and spring blooms. Biological responses at this time scale include growth, distribution, development of energy reserves, reproductive output and reproductive success. There has been a heavy reliance on environmental data at this scale for retrospective studies.

Inter-annual environmental factors have biological responses similar to most of those associated with the seasonal time scale listed above. The principal difference between environmental factors at these two

Table 1. Time, Space and Fish Scales

A. TIME SCALES

Type	Period	Environmental Factors	Biological Responses
Weather	1-5 days	Storms, Floods.	Behavior, Distribution, Early life history effects
Seasonal	2-3 months	Winter turbulent mixing, Offshore transport, Spawning season temperature, Spring bloom.	Growth, Energy reserves, Reproductive output, Larval drift, Reproductive success
Inter-annual	1-2 years	El Niño phenomenon	Growth, Recruitment, Distribution
Regime	5-30 years	Shifts in oceanic circulation, Fleet development	Carrying capacity changes, Overexploitation effects
Geological	100+ years	Erosion and sedimentation, Sea level changes, Plate movement.	Extinctions and evolution

B.SPACE SCALES

Type	Scale	Fishery Research Programs
Microscale	.001-1 km.	SPACC (GLOBEC Program)
Mesoscale	5-200 km	Georges Bank GLOBEC Program, FOCI, Tiburon Rockfish Surveys
Regional	500-2000 km.	CalCOFI Program, RACE trawl surveys, Most fishery population analyses (by default)
Basin scale	5000-20000 km.	SWFSC Albacore Program (by default), Regime Group (larger than individual stocks)
Global	The whole ball of wax	The World's fishery

C. FISH SCALES*

Species	Age at Maturity (yr)	Multiple Spawner	Maximum Age (yr)	Maximum Size (cm)	Annual Movement (km)	Stock Area (km)
Anchovy	1-2	yes	7	22	400	600
Herring	2-3	no	9	40	300 ?	400
Sardine	1-3	yes	14	34	2000	2500
Mackerel	1-2	yes	11	64	2500	3000
Albacore	5-7	yes	15 ?	150	7000	9000
Bocaccio	3-6	no	40	92	100 ?	1000
Splitnose	6-9	no	80	40	1 ?	1000

* Examples are all from the California Current Region

scales is that factors at the seasonal scale may be the result of environmental variations at the more local, intermediate spatial scales, whereas environmental variations at the annual scale, for example El Niño phenomena, are more likely to be the result of environmental process operating at the larger space scales.

Regime scale environmental factors are, almost by definition, associated with large scale shifts in oceanic circulation, upwelling, and vertical mixing. At this time scale it may be difficult to separate abiotic environmental process, biotic environmental processes, density-dependent processes and overexploitation effects; however, this time scale is the one most often associated with the failures of marine fishery management.

Space Scales

For the purposes of this report spatial scales have been divided into four usable categories; micro, meso, regional and basin scales (Table 1). It should also be noted that the temporal and spatial scales are assumed to be linked (i.e., storms are associated with micro and meso spatial scales and El Niño events are associated with regional and basin spatial scales). This does not necessarily imply that events which occur at other scale combinations (i.e., a mid-Atlantic strike of a large meteor; microscale temporal and basin scale spatial scales), are unimportant, only that they are largely outside of the realm of fishery research and management.

Large fisheries field programs have been designed to sample on a broad range of spatial scales and these scales were heavily influenced by the fishery paradigms in vogue when the programs were started. Older programs such as the CalCOFI Program of the Southwest Fisheries Science Center and the Resource Assessment and Conservation Engineering trawl surveys of the former Northwest and Alaska Fisheries Center were designed to cover the distribution of wide-ranging stocks and they are therefore regional in spatial coverage. Others such as the North Pacific Albacore program were designed as basin scale programs due to the even larger stock area occupied by albacore. More recent field programs such as the Shelikof Strait (FOCI) and Georges Bank (GLOBEC) programs have focused on meso or sub-regional spatial and the smaller temporal scales in response to early life history paradigms (i.e., as in "critical early life history stages"). Planning is currently underway in the Small Pelagics and Climate Change Program (SPACC; GLOBEC) to study climate change scale processes by examining daily zooplankton production and daily somatic growth rates of small pelagics. Here comes that meteor again.

Fish Scales

Although it is seldom mentioned, it is just as important to know the scales at which fish **populations** interact with their environment as it is to know the scale at which abiotic oceanic processes occur. The emphasis on fish populations rather than fish is critical as fishery management is based on the population response not on the individual response. For example, a large scale warm anomaly could be viewed as negative for individuals at the lower latitude edge of a stocks range and positive for individuals at the high latitude edge. Very precise, smaller scale process oriented studies in the two locations would, in this case, be expected to give opposite results to the same environmental forcing.

Fishes have evolved a wide range of life history characteristics which allow their populations to minimize the adverse effects of environmental variability at various time and space scales. These include differing longevity, age at maturity, fecundity, body size, mobility, and even large differences in the size of the geographic area that they occupy (Table 1). Some clupeid stocks spawn a single batch of eggs per year at a single site at essentially the same time each year. (i.e., Pacific herring, Clupea pallasi), others spawn 40 batches per year at a multitude of sites (i.e., South African sardine, Sardinops sagax ocellata) Some species mature at a young age, can fully develop and spawn a batch of eggs in just 24 hours, or two batches in 48 hours, and often move thousands of kilometers in a matter of months (i.e., Pacific mackerel, Scomber japonicus). Others have a delayed age at maturity, are viviparous, take several months from insemination to extrusion of larvae and they may move less than a kilometer in 50 years (i.e., splitnose rockfish, Sebastes diploproa). In quite different ways both Pacific mackerel and splitnose rockfish have life history characteristics which largely buffer their populations from environmental variation at the smaller scales (Table 1). In contrast, the Pacific herring is likely to be affected by environmental events at the smaller time and space scales as well as those at the larger scales.

Table 2. Scales vs. Fishery Paradigms

Critical Stage Paradigm, Early Life History (ELH) Paradigm
Concept: Hjort, (single spawners, favorable ELH window)
Weather time scale (i.e., intense storm, turbulent mixing)
Mesoscale - Sub-regional spatial scale (i.e., storm spatial scale)
Concept: Lasker, (multiple spawners, i.e., not enough forage for first feeding)
Seasonal time scale
Regional spatial scale
Larval Transport Paradigm
Concept: Various researchers, (crucial larval drift patterns)
Weather to Seasonal time scales
Regional spatial scale
Equilibrium Carrying Capacity Paradigm
Concept: Environment with normally distributed white noise
Concept: With red and white noise
Concept: With edge effect (i.e., temperature tolerance)
Weather - Seasonal time scales
Regional spatial scale
Regime Paradigm
Concept: Jyungman*, (large scale oceanographic cycles)
Decadal time scale
Regional, Basin or Global spatial scale

*Jyungman, A. 1880. Contribution toward solving the question of the secular periodicity of the great herring fisheries. U.S. Comm. Fish and Fisheries, Rept. of the Commisioner for 1879 p. 497-503.

Fishery Paradigms

Following the above pattern the most common present paradigms concerning the effects of the environment on fish populations are divided into four categories; critical stage, larval transport, equilibrium carrying capacity, and regime paradigms (Table 2). A fifth very important paradigm, "it's all due to overfishing," was excluded from the classification scheme since it has no environmental component. Any readers should note that when the boundaries of one of these paradigms is extended far enough it enters the boundaries of what another reader would classify as another of the paradigms. In addition, the critical stage and larval transport paradigms focus on recruitment and they are popularly limited to the early life history stages when mortality rates are at a maximum. Recruitment, however, is not exclusively a ELH problem since it is also critical that a fish survive the juvenile and pre-adult stages before it can be recruited to the adult population. Note that it is not uncommon for recruitment to the adult population to take 5 or more years. It is also very important to realize that modeled populations generally only have to cope with one of the paradigms whereas real populations must cope with all of them.

The critical stage paradigm can be subdivided into two quite different problems. The first primarily deals with higher latitude species such as herring which mature a single batch of eggs per year, have quite short and precisely timed spawning seasons, and deposit all of their eggs at a single site. The second deals with subtropical or tropical species such as sardine or mackerel, which produce numerous batches of eggs over spawning seasons lasting from 3 months to the entire year, and individuals may spawn over a very wide geographical area. In the first case it would be expected that weather time scale and meso spatial scale environmental variations could play a key role in the determination of recruitment. In the second case these scales are less likely to influence recruitment since there is a continuum of critical stages occurring over a broad expanse of time and area. A very large amount of early life history research has been carried out under this paradigm in the last decade. To date the majority of this work has been utilized in the real time, descriptive mode and there has been little practical application of retrospective analyses. This may primarily be due to the fact that few of these ELH studies have been carried out for a long enough period of time for retrospective analyses to be more than anecdotal.

The larval transport paradigm has been applied to a wide range of species and its basic concept is that variations in wind and thermohaline-driven transport between a species spawning and nursery grounds is a major factor in the determination of recruitment. The principal environmental data sources which have been used to test this paradigm are wind-speed time series derived from meteorological models (available for meso (1946-present) and weather (1967-present) scale retrospective analyses. Weather to annual scale time series for ocean circulation, which include the thermohaline driven circulation, have generally not been available to fisheries researchers in the past, and sea level height has been extensively and successfully used as a proxy for the intermediate to larger time and space scales. Recent and proposed coupled ocean-atmosphere models are well suited to this paradigm and the usage of these models to produce mesoscale hindcasts extending back to the 1950s will allow a great expansion of retrospective studies under this paradigm.

The carrying capacity paradigm is of course borrowed from terrestrial ecology and its original usage is based on the concept of a steady-state system. For the present classification scheme, its meaning is limited to the steady state, or equilibrium, carrying capacity concept. Under this paradigm environmental effects are viewed as variance about a mean (the carrying capacity). This still allows a very wide range of definitions. For example the variance could come about through temporal variation in the "quality" of a given geographical region. It could occur through geographical expansion and contraction of the region with a constant "quality". For example, a subtropical species which lives adjacent to a large area that has temperatures just outside of the species temperature tolerance could temporarily occupy a much larger geographic range, with a greatly increased carrying capacity if the region experiences anomalously warm temperatures. The carrying capacity paradigm differs from the critical stage and larval transport paradigms in that carrying capacity is often viewed as a process which limits the adult component of the population rather than the early life history stages. These stages are not necessarily excluded from the paradigm, however, as the carrying capacity limits could be acting upon ELH stages or juveniles.

Typically environmentally induced variance from the equilibrium carrying capacity concept is considered to be white noise at the seasonal or interyear time scale. Introduction of autocorrelation at the longer time scales alters the concept and when this autocorrelation approaches decadal time scales the carrying capacity paradigm becomes the regime paradigm. The basis of the regime paradigm is that there are natural decadal, or longer, shifts in basin, or global, scale environmental conditions which result in alterations in the carrying capacity for the dominant, and perhaps other fishes, of a region.

Retrospective Environmental Data Requirements

The many fisheries oceanography workshops which I have attended over the past two decades all had two things in common. None of them stated which specific environmental data are needed for fisheries and they all developed a similar shopping list of environmental variables which included everything that anyone present could think of. I have therefore attempted to make a short list of environmental variables I believe would be useful to a wide range of fisheries and other biological researchers engaged in retrospective analyses and modeling. In each case the utility of the time series will be greatly enhanced by each year that it can be extended into the past. In each case NOAA, the US Navy, and US Academia currently have programs which are presently producing, or have the capability to create the time series.

1. Monthly or bimonthly time series of the geostrophic transport of the major current systems of interest to US fisheries (i.e., the Alaska, California, Labrador, Loop, and North Pacific Currents and the Alaska and Gulf Streams). This will require hindcasts of nested, coupled ocean-atmosphere models. As a comment, it might be noted that if NOAA cannot provide fisheries management with accurate time series of **the principal oceanographic feature** of each of our major marine ecosystems, we cannot expect to either understand or manage our fisheries.

2. Daily time series of surface winds at mesoscale spatial resolution for the US EEZ. This information is presently available both as raw data (COADS and meteorological buoys) and model output from US Navy and NOAA meteorological models. Incremental increases in the accuracy and availability of products should be of very high priority to NOAA.

3. Monthly time series of sea surface temperature are currently available and should be maintained (COADS, shore stations, and model output). It is particularly important to maintain the existing shore stations (SST and sea level) **which have long time series.**

Perspective

Most of the models and analyses presently utilized for fisheries management are retrospective. Although most researchers believe that environmental factors have major effects on fish populations, many (and probably most), of the retrospective analyses and models utilized for fisheries management do not include any environmental input. Although most researchers believe that inter-species interactions have major effects on fish populations there is a similar lack of utilization of interspecific information in fisheries management. The track record of fisheries management is dismal and, although it is obvious to those of us who have observed the process for several decades, much of the problem is caused by an institutional failure to make the hard choices; it is also obvious that the track record of fisheries predictions is nothing to be proud of.

The vast majority of current research resources has been directed into large process-oriented field studies which are very unlikely to provide management quality results within the next decade; it is my opinion that many, perhaps most, of these studies will not, and probably should not, be carried out for a long enough period of time to provide such results. Meanwhile the basic fishery sampling programs, which have never been of even moderate priority within many of the NMFS Regions, are providing an inadequate fishery data source to the small cadre of mathematically adept (but not necessarily oceanographically or biologically adept), modelers that are providing the information presently utilized for fishery management decisions.

How can NOAA/NMFS alter present trends? Let's have a workshop!

NOAA Technical Memorandum NMFS

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CHANGING OCEANS AND CHANGING FISHERIES: ENVIRONMENTAL DATA FOR FISHERIES RESEARCH AND MANAGEMENT A WORKSHOP

George W. Boehlert[1]
James D. Schumacher[2]

[1]Pacific Fisheries Environmental Group (PFEG)
Southwest Fisheries Science Center
1352 Lighthouse Avenue
Pacific Grove, California 93950-2097

[2]NOAA/OAR
Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle, WA 98115-0070

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